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MONITORING OF TORSIONAL VIBRATION OF A CRANKSHAFT BY INSTANTANEOUS ANGULAR SPEED OBSERVATIONS

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Abstract

Continuous monitoring of diesel engine performance under its operating is critical for prediction of malfunction development and subsequently functional failure detection. Analysis of Instantaneous angular Speed (IAS) of the crankshaft is considered as one of non-intrusive and effective method of detection of combustion quality deterioration. The paper contains presentation of attempt of monitoring of piston engine's crankshaft torsional vibrations by measurement of Instantaneous Angular Speed at free and power output ends of the engine. It is assumed that calculation of differential value of angular distance run between both ends in the same time shall give the picture of torsion angle magnitudes and phases of the peak values. Fir carrying out such measurements, high frequency of sampling was required. The angular speed measurements is to be done utilising two optical sensors for reading and two perforated discs mounted at shaft's ends playing the role of speed signal emitters. In the paper is presented description of the measurement system and explanation of its mode of work. It is also shown analysis of measurement accuracy, way errors elimination and method of signals runs filtration. Presented results of experiment derives from test cycle carried out using laboratory stand of Gdynia Maritime University equipped with 3- cylinder self - ignition engine, powering electric generator.

Keywords: *diagnostics, diesel engine, torsional vibrations, torque and angular speed.*

1. Introduction

Diesel engines are one of the most critical mechanisms having impact on safety of shipping. Unpredicted failures of engines, installed on board as main propulsion or electro-generators units can result with serious consequences, jeopardizing human life and environment [6]. One of the most common problems occurring during diesel engines operation are malfunctions of fuel injection systems and subsequently problems with torsional vibrations and revolutionary speed uniformity. Moreover, as far as electro-generators are concerned, irregularity of rotational speed can affect quality of delivered electric energy (frequency stabilization). Detection of the piston – sleeve set giving no proper contribution to the total engine's torque value is possible in way of measurement of in-cylinder pressure using electronic or mechanical indicators. That method, although very effective has some inconvenience. Firs one is related to an engine construction – one has to have indicator cocks at every cylinder, second one is due gauges vulnerability, high temperature and exhaust gases pollution do not let continuous monitoring. Above presented facts leads to the conclusion that any other way, free from presented inconveniences shall be accepted for practical implementation [1].

In internal combustion piston engines, reciprocating movement of pistons is converted to rotary movement of the crankshaft. The angular speed is strongly affected by tangential force coming from gas pressure and vertical imbalance inertial forces induced by reciprocating masses of piston and connecting rod. The character of acting forces let assume that IAS can be utilized for detecting engine faults related to combustion process [2, 4]. Because of sequential ignition in cylinders and differences of combustion quality (i.e. burning process's speed and duration, heat emission, pressure expansion) occurring between cylinders, angular speed of a crankshaft is not uniform.

Variations of instantaneous angular speed value are reflecting level of unsteady character of subsequent pistons contribution [7].

The main goal of carried out investigation was answer the question whether IAS signal coming out from both ends of the crankshaft can be a source of information about torsional vibration of the shaft due to combustion irregularity and whether level of shear stress can be measured and controlled at working engine, under different levels of load and rotational speed, using IAS as a signal bearing information about torsional twist of an crankshaft.

2. Description of IAS measurement system and characteristics of the test rig

For measurement of Instantaneous Angular Speed in both ends of the shaft, line was implemented encoders in form of perforated disc with windows placed at edge of the disc. All windows have the same dimensions and angular distance between them is 2°. Number of windows is 90, and then windows are separated by 90 “teeth” with the same angular span of 2°. Rotating disc cuts laser ray pointed at disc’s edge in middle of windows’ zone. Measurement head, “u” shaped form, consist of laser from one side and photodiode at opposite arm. Laser impulses, emitted with frequency of 16 MHz going through windows creates signal with value “1” and stopped by tooth gives blind signals value “0”. This mode of operations lets measure time of passing angular width of tooth and window, in form of number of registered impulses. Above presented mode of operations must lead to the conclusion that accuracy of preparation of windows and equality of their dimensions are crucial for accuracy of measurements. In practice that inconvenience can be partly omitted by taking for calculation an angle of a pair window-tooth, eventually broader of narrow window’s size is compensated by tooth dimension because total angular distance must be equal to 360° [2].

In order to mark the position of the disc in correspondence to the crankshaft position, the trigger in a form of one additional window (slot) narrow and asymmetric is to be placed in the zone of one tooth. That slot must be placed at position “cutting” laser ray when piston in first cylinder is in TDC (Top Dead Centre). It lets allocate every part of IAS record to crankshaft angle and specific cylinder, what is absolutely necessary for further diagnostic analyses.

The angular speed calculation depends of number of windows around the disc, and can be presented in form of formula (1).

$$\omega = \frac{\frac{2\pi}{w}}{i \cdot f} \left[\frac{rad}{s}\right], \tag{1}$$

where:

ω – angular speed,

w – number of pairs “window-tooth”,

i – number of impulses register for pair window-tooth,

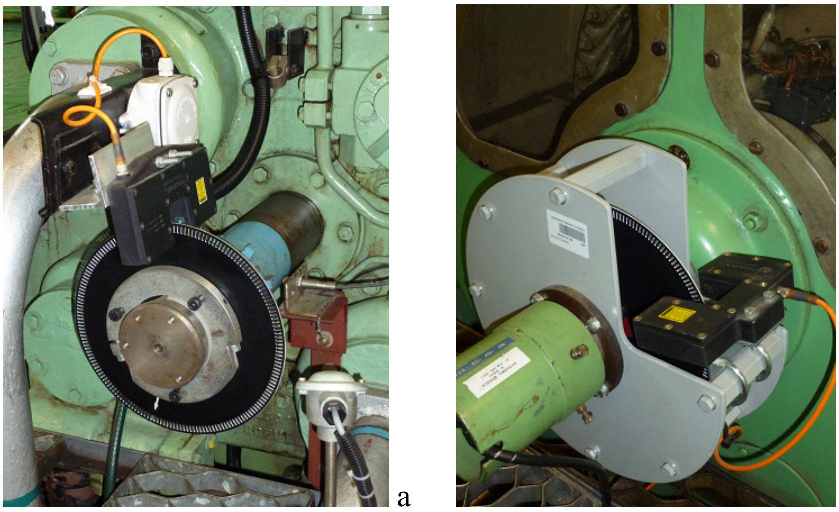
f – frequency of laser emitter.

Because of high frequency of the emitter, presented system can be implemented for speed measurement of high-speed engines (revolutionary speed of 1200 – 3800 rev/min). Assuming sensitivity of photodiode at level $\mp$ 10 impulses, accuracy of measurement depends of engine’s revolutionary speed and for medium speed diesel engines typical for marine electro – generators sets reaches the level of 0.015%.

Mounting of the discs and measurements heads are presented in Fig 1.

2. Description of experiment’s assumptions and measurements plan

Experimental measurements were carried out at laboratory engine, which was 3 cylinder, medium speed (600 to 750 rev/min) self-ignition marine engine powering electro-generator. In Fig. 3 is presented model of masses being in reciprocating and rotating movement. It was assumed that parts of crankshaft between connecting rods and flywheel were elastic and undergoing torsional twist, but flywheel and rotor of the electro generator was reduced to one mass [1, 3]. That let consider that movement of the end of generator's shaft is equal to end of engine's crankshaft at point of flywheel. Thus measurement disc placed at end of the generator reflect movement of the flywheel end.



a b

Fig. 1. Master disc A mounted at engine's free end (a) and sleeve disc B mounted at generator shaft end (b)

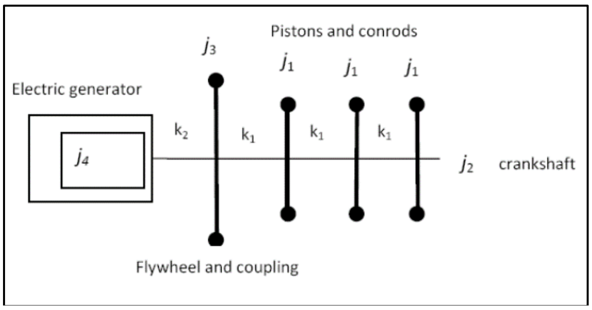


Fig. 2. Scheme of mass displacement for torsion calculation

Difference between angular positon of reference points A and B marked at both ends of the crankshaft gives the torsion magnitude Φ measure and lets to calculate stress value τ (see Fig. 3).

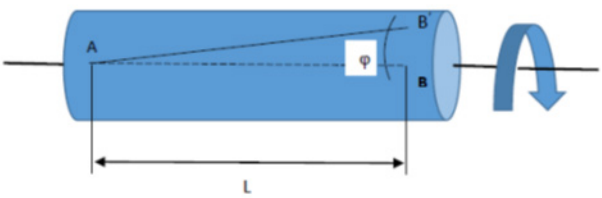


Fig. 3. Model of shaft's torsional displacement

Mean Instantaneous Torsional Angle magnitude was calculated as a difference between distance done in the same time by points A and B. Differential angle value is due to different angular speed caused by torsional movement of the shaft. Because of mode of obtained signal i.e. number of impulses, only average value of speed during assumed angular zone can be measured. In our case as the reference instantaneous angular speed were taken speeds of subsequent zones covering pair of window-tooth of free end disc. The instantaneous value of angular speed difference was calculated using formula (2):

$$\delta\omega_n = \frac{2\pi f}{w}\left[\frac{1}{i_n} - \frac{1}{j_n}\right]\left[\frac{rad}{s}\right], \tag{2}$$

where:
n – index of subsequent window – tooth pair,
i – number of impulses registered at disc A,
j – number of impulses registered at disc B,
w – number of pairs tooth-window,
in addition, displacement Φ between points B and A taken as the difference of angular way done by both points, in reference to crankshaft angle position α is presented in form of formula (3):

$$\Phi = \sum_1^n \frac{\omega_{Anf}}{i_n} - \sum_1^n \frac{\omega_{Bnf}}{j_n}\ [rad]. \tag{3}$$

For example, let take a number of impulses registered for window-tooth zone of free end as 5000 and number of impulses registered for opposite side was 4500, and 90 pairs window-tooth around the disc, average deflection value in the assumed zone is 0.0448 rad (0.28°).

Calculation of angular way difference for subsequent zones gives discrete picture of torsional vibrations. Presented approach to the problem is simplified to the single node torsional model. It is assumed that single node torsional model shall be enough accurate [3].

Number of impulses registered for tooth or window passing through laser ray for the same angular speed, strictly depends of their width, what is a function of disc diameter. It means that bigger diameter gives more impulses dedicated to certain window (tooth) and increase possibility of exact measurement crankshaft rotating with very high revolutionary speed. From practical point of view, too big discs can be awkward for mounting because of space limitation, what spoils general idea of designing a system characterised by compact construction and easy for installation.

When minimum required number of impulses registered for one window passage assumed as level giving proper detection of occurrence of deviations as 1000, minimum window width because of manufacturing constraints – 1 mm, 90 windows and 90 teeth (2°) around disc's edge and frequency of emitter equal to 16 MHz, one can calculate disc diameter and angular speed enabling proper measurement .

Maximum linear speed would be:

$$v_{max} = \frac{s}{t} = \frac{s}{w \cdot f}\ [m/s], \tag{4}$$

$$v_{max} = \frac{0.001 \cdot 16000000}{2 \cdot 90} = 88.88\ [m/s],$$

moreover, maximum angular speed:

$$\omega_{max} = \frac{\frac{2\pi}{360} \cdot 2}{\frac{1000}{16000000}} = 558\ \left[\frac{rad}{s}\right].$$

Above presented calculations ensures accurate measurement for all range of piston engines from low (100 rev/min) to high speed (3600 rev/min). Maximum linear speed is necessary for calculation of the number and dimension of slots for big diameter discs mounted around big diameter shafts.

2.1. Verification of method's accuracy

Because of comparative nature of measurements, is absolutely necessary to verify level of potential deviations between data coming from both ends of the shaft. Despite of torsional character of revolutionary speed, average angular speed of two ends of the shaft must be equal and arithmetical sum of instantaneous torsional deflections must be equal to 0.

In order to verify above, several measurements under various loads were carried out. Results are presented in form of irregularity deviation index γ calculated as proportion of differential value to mean value (formula 5).

$$\gamma = \frac{2(\omega_A - \omega_B)}{\omega_A + \omega_B}, \tag{5}$$

where:
ω_A – angular speed of the disc A [rad/s],
ω_B – angular speed of the disc B [rad/s].

Obtained results of angular speed deviations between front and rear discs are presented in Tab. 1. It enables coming out with the conclusion that error is very low, can be omitted, and proposed method of angular speed is right and accurate.

Tab. 1. Values of deviation index calculated for mean values of 1 revolution and 10 revolutions

Load	Angular speed disc A		Angular speed disc B		**Deviation index γ**	
	mean of 1 rev.	mean of 10 rev.	mean of 1 rev.	mean of 10 rev.	mean of 1 rev.	mean of 10 rev.
100 kW	79.13621	79.10985	79.1456	79.10509	**1.2E-4**	**6.01E-5**
140 kW	79.06436	79.04746	79.05816	79.04055	**7.8E-5**	**8.7E-5**
220 kW	78.94818	79.00442	78.91894	79.00359	**3.7E-4**	**1.05E-5**

3. Results of experiment

Proposed method of torsional vibrations was verified during set of measurements carried out at test stand. Obtained results were processed and analysed in respect of its credibility and accuracy.

Measurements were conducted according to verification plan including engine's work under different loads from 50 up to 220 kW, and setting up different revolutionary speed in span of 650 to 750 rev./min. Implemented registration block ETNP-10 enable register of 10 subsequent revolutions, what gives five working cycles of four stoke engine covering 720 degrees of crankshaft revolution.

As base value for analysis were taken values of magnitude of torsional displacement angle Φ. Torsion values were compared in several combination i.e. difference magnitudes between subsequent cycles and general form of torsion characteristics, comparison between different revolutionary speed and different loads. Finally, torsional stress values were calculated and analysed. Results of experiments are presented in subchapter below.

3.1. Magnitudes of torsional deflection

The character of torsional deflection registered for speed of 650 rev/min (68.4 rad /s) and low load (50 kW) is presented in Fig. 4. Analysis of 10 revolutions runs shows that fluctuation of twist occurs within one cycle encompassing two revolutions and low frequency sinusoid causing changing of torsion's sign occurs as well. It was confirmed by FFT analysis, what showed high magnitude for frequency around 1.66 Hz what refers to 1/7 basic frequency of revolutionary speed. Positive values means that point at disc A was "in before" point B, negative value refers opposite situation. Analysis of run consisting of 10 subsequent revolutions shows those changes of magnitudes value as well as direction of torsion occurs. Comparison presented in Fig. 5 shows that differences between torsional vibration characteristics of subsequent cycles, concern magnitude but accordance of phase of peaks could be noticed. Value of maximal magnitude difference is at level of 25% of maximum torsion.

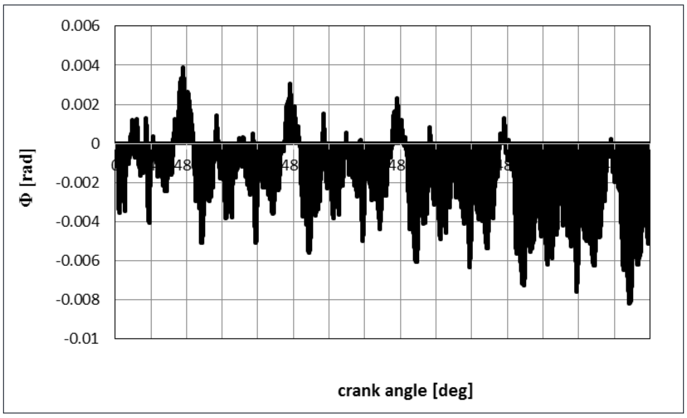


Fig.4. Shaft's torsion angle Φ registered for 10 subsequent revolutions. Engine's load 50 kW, rotational speed 650 rev/min

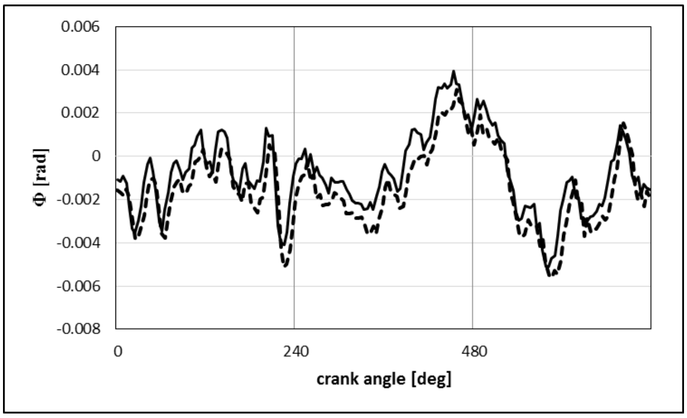


Fig. 5. Comparison of torsion angle Φ of the shaft, for two subsequent cycles under constant load and speed (one cycle 720 degrees CA). Engine load 50 kW and speed 650 rev/min

Increasing of engine's load and revolutionary speed is causing changes of torsional vibration characteristic in respect of magnitude, peak phase and torsion sign as well. Analysing picture presented in Fig. 6, one can see that peaks of torsion and curve shape reflect run of excitation force due to combustion pressure in three cylinders. In addition, lower value of difference between subsequent cycle runs can be observed.

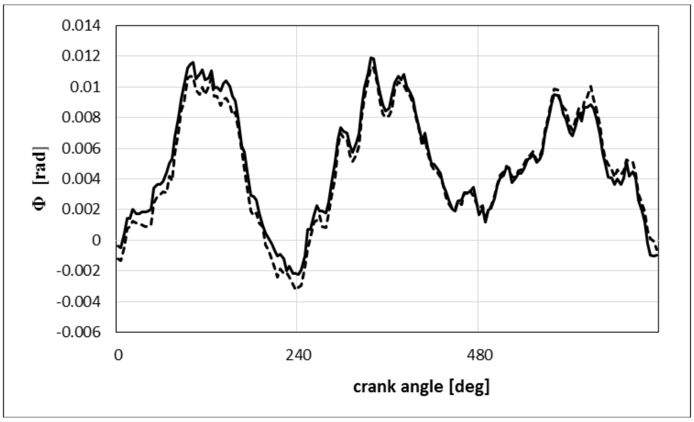


Fig. 6. Comparison of torsion angle Φ of the shaft, encompassing two subsequent cycles under constant load and speed (720 degrees CA). Engine load 220 kW, speed 700 rev/min

Torsional deflection peaks value is more stabilised and fluctuation of peaks envelop for 10 revolutions occurs, anyway is not as significant as was observed for low load (see Fig. 7).

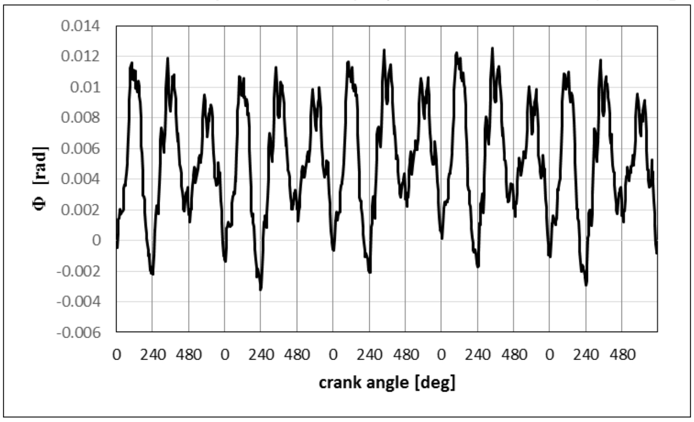


Fig. 7. Picture of torsional twist registered for 10 subsequent revolutions. Engine load 220 kW, speed 700 rev/min

Character of shaft's twist has its reflection in shear stress value what is presented in Fig. 8 and Fig. 9. Stress in case of low load shows rising tendency, and reaches value of 25 MPa. Higher load is characterized by higher stress value - 38 MPa, but maximum of subsequent cycles keeps lower fluctuation.

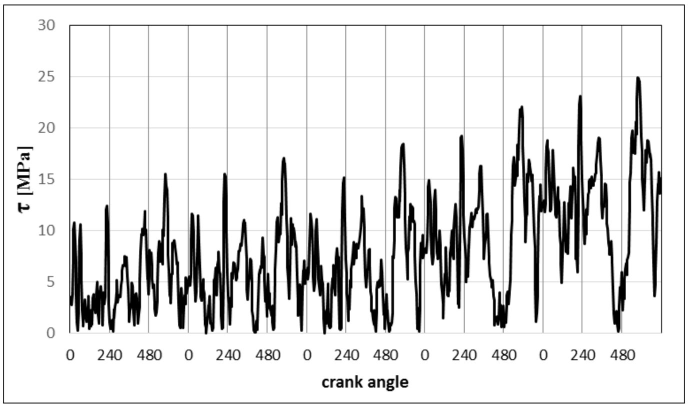


Fig. 8. Waveform of shear stress, registered during 10 subsequent revolutions. Engine load 50 kW, speed 650 rev/min

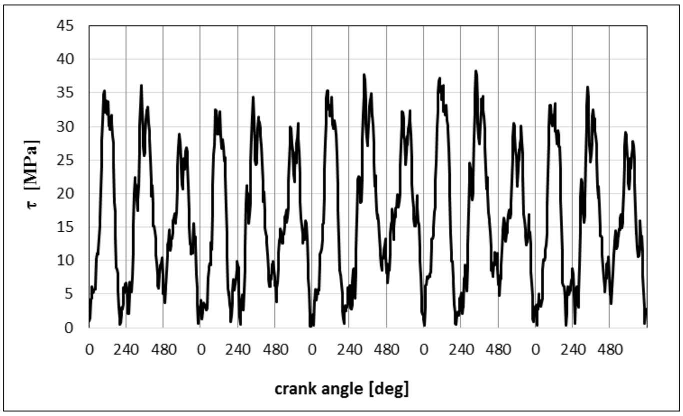


Fig. 9. Waveform of shear stress, registered during 10 subsequent revolutions. Engine load 220 kW, speed 700 rev/ min

4. Summary

Primary analysis of received results is quite optimistic. Accuracy of the method is very high, and rough errors caused by fabrication inaccuracy are eliminated by taking as the basic module zone of two pairs of slot-tooth. This way eventually, differences between width teeth due to fabrication are compensated. Very important was result of comparison of average speed of disc A and B what ensure us that system of simultaneous registration of impulses from both ends by programmable logic controller is correct. It is assumed that presented method of torsional vibration registration will be used for diagnostic purposes. Any interferences of combustion or friction shall be reflected by character of torsional vibration and be detected comparing with template spectrum. Further action of investigation will be directed to recognition of malfunction, and, what seems to be necessary, extension of length of records up to 20 revolutions what will need program set up.

References

[1] Xiang, L., Yang, S., Gan, C. *Torsional Vibration Measurements on Rotating Shaft System Using Laser Doppler Vibrometer.* Optics and Laser in Engineering, 50, pp. 1596-1601, 2012.

[2] Dereszewski, M., Charchalis, A., Polanowski, S. *Analysis of diagnostic utility of instantaneous angular speed of a sea going vessel propulsion shaft*, Journal of KONES, Vol. 18, No 1, 2011.

[3] Murawski, L., Charchalis, A. *Simplified Method of Torsional Vibration Calculation of Marine Power Transmission System,* Marine Structures, 39, pp. 335-3349, 2012.

[4] Charchalis, A, Dereszewski, M., *Processing of instantaneous angular speed signal for detection of a diesel engine failure,* Hindawi Publishing, 2013.

[5] Dereszewski, M., *Wykorzystanie modelu dynamicznego silnika Sulzer 3Al25/30 do symulacji wpływu zmian obciążenia i uszkodzeń na fluktuację prędkości kątowej*, Zeszyty Naukowe AM, Nr 81, Gdynia 2013.

[6] Piotrowski, I. Witkowski, K., *Okrętowe silniki spalinowe*, Trademar, Gdynia 2003.

[7] Werner, J. Wajand, J, *Silniki spalinowe małej i średniej mocy,* Wydawnictwa Naukowo-Techniczne, Warszawa 1983.